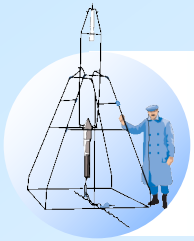
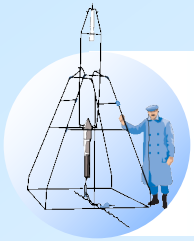


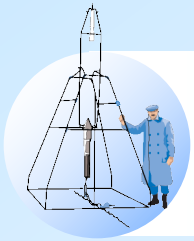
Development of Advanced Spacecraft Thermal Subsystems

Jeffrey R. Didion
Senior Thermal Engineer
Manager, Nanotechnology Facility



Technical Overview

- **Fundamental Research:**
  - *Electrically Driven Liquid Film Boiling* **NASA HQ SLPSRA Division NNX12AR32G (Yagoobi/WPI & Didion)**
  - *Self-Sensing Thermal Management Using nano-enhanced Polymers* **NSTRF FY13 (Bruck & Sauerbrunn/UMD & Didion)**
  - *Study of Micro/Nano Scale EHD-Driven Flow Distribution Control and Heat Transfer Enhancement for Thermal Control Systems* **NSTRF FY14 (Talmor & Yagoobi/WPI & Didion- NSTRF Mentor)**
- **Flight Hardware: Electrically Driven Liquid Film Boiling**
  - **ISS Fluids Rack – FY21**
  - **Micro-Scale Fundamental Resaearch**

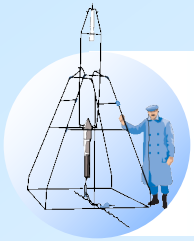


NASA Relevance

- **NASA Space Technology Roadmaps:**
  - *TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems*
    - *TA 5.5.2 Power Efficient Technologies (Ka Band amplifiers)*
    - *TA 5.2.6: Antennas (Ka Band Phased Arrays)*
    - *TA 5.5: Integrated Technologies – Radio Systems (reduced SWaP)*
  - *TA 14: Thermal Management Systems*
    - *TA 14.2.1: High Heat Flux Acquisition @ constant Temperature*
    - *TA14.2.2: Advanced Efficient Pump Techniques; specifically calls out EHD pumping*

- **Decadal Survey Missions**

  High Power RF Amplifiers (HPA) have thermal challenges that limit microwave (communication and radar) performance
  - *Aerosol, Cloud and Ecosystem (ACE)*
  - *Snow and Cold Land Processes (SCLP)*

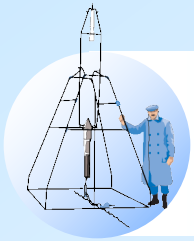


NASA Technology Point of Infusion

Integrated Radar Subsystem ACE & SCLP

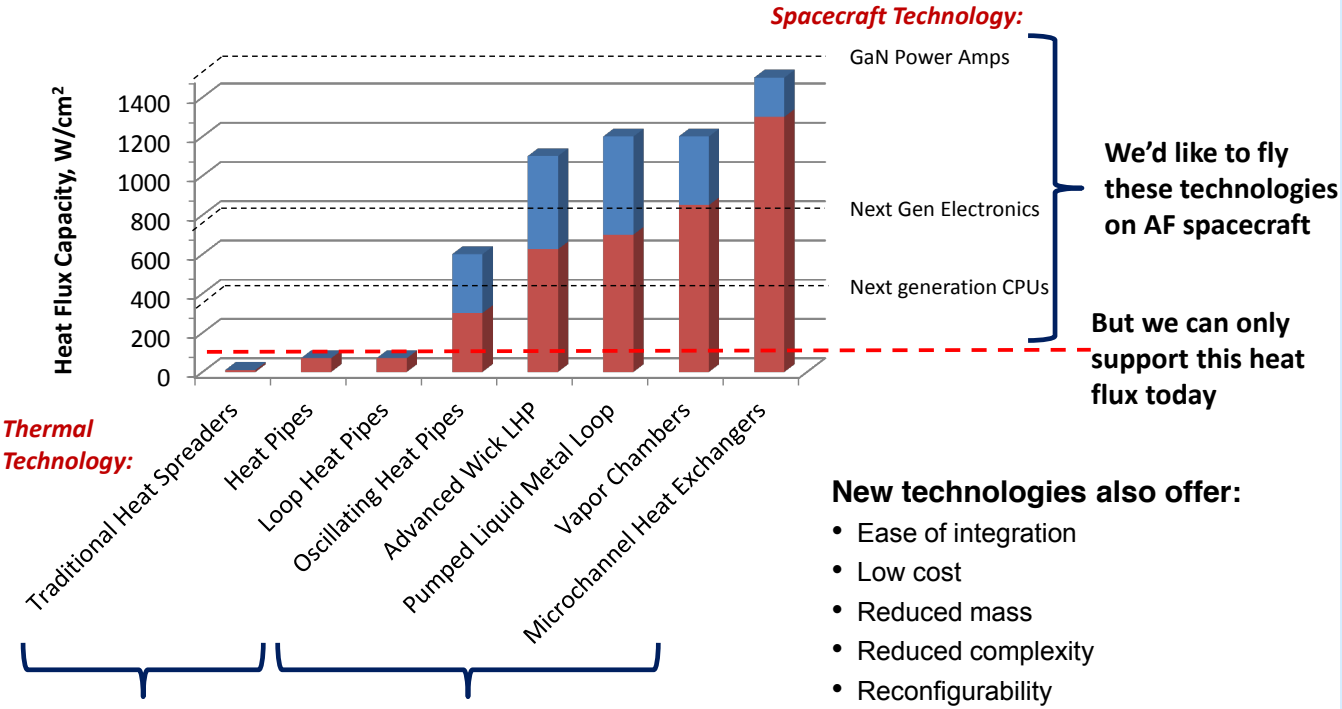
- *High Power Amplifiers (HPA) performance is thermally limited; Improved thermal management for GaN based amplifiers will achieve higher instrument sensitivity via higher duty cycle.*
- *Improved thermal management of high power RF signals alleviates the current frequency limitations (set by International Agreement) and enable the development of Multi-Use Systems*
  - » *Identified Ka Band (35 GHz) transmit/ receive module performance limitations due to thermal management*

- *Enabling Technology: Improved transmit/receive module will permit use of synthetic aperture radars*



High Heat Flux Thermal Management

High Heat Flux Electronics Cooling



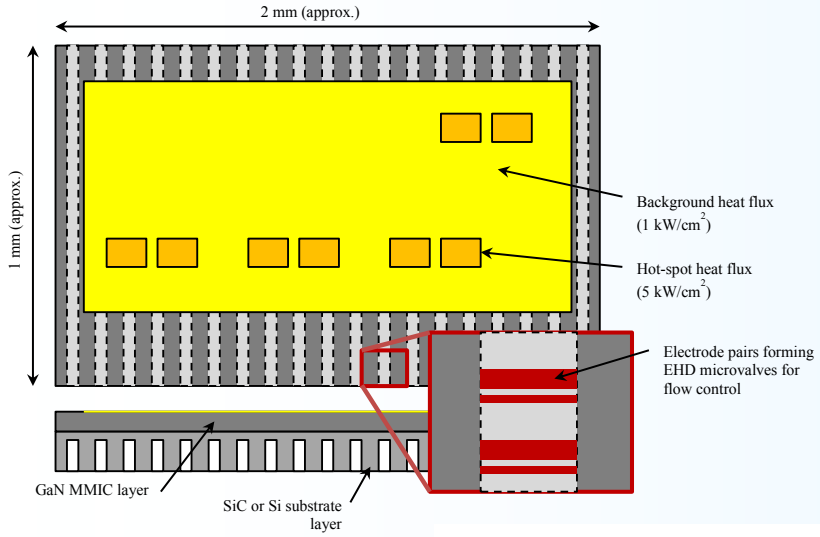
New technologies also offer:

- Ease of integration
- Low cost
- Reduced mass
- Reduced complexity
- Reconfigurability
- Thermal Stability

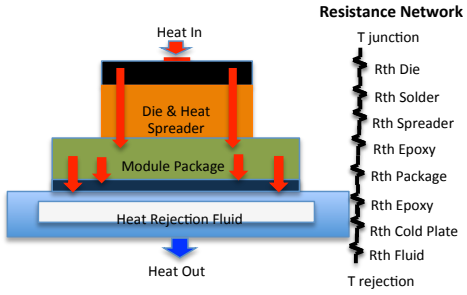
7

Courtesy of Andrew Williams, USAF

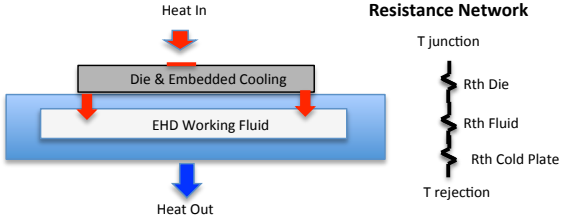
High Temperature Heat Acquisition: Reduced Thermal Resistance



Reduced Mass and Volume of Chip
Reduced Thermal Resistance
High Temperature Heat Acquisition

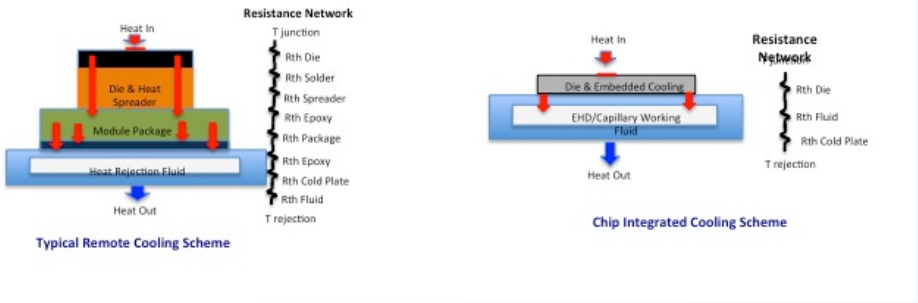


Typical Remote Cooling Scheme

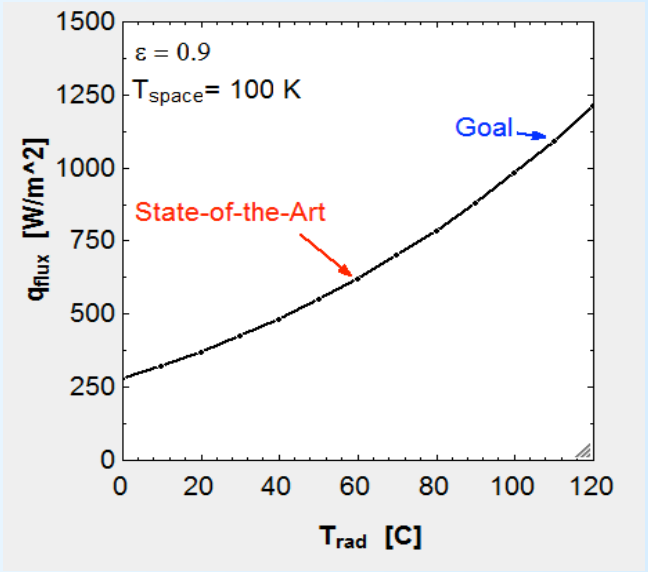


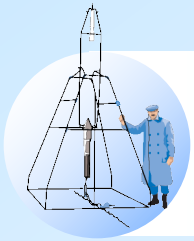
Chip Integrated Cooling Scheme

High Temperature Heat Rejection



Higher Heat Rejection Temperature
Lower System Thermal Resistance





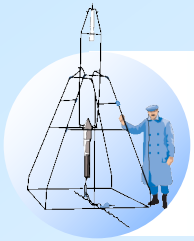
Electrohydrodynamic (EHD) Phenomenon

Interaction between electric field and flow field

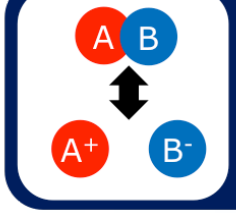
$$\boldsymbol{f}_e = \rho_e \boldsymbol{E} - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[E^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \rho \right]$$

Coulomb Force

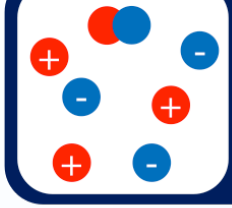
Polarization Forces



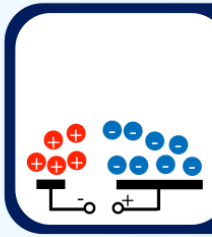
EHD Conduction Phenomenon



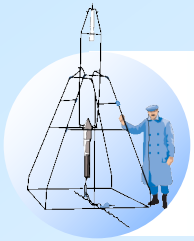
Molecules dissociate into positive and negative ions, while ions recombine into neutral molecules. When electrical field intensity is low, dissociation & recombination rates are in dynamic equilibrium.



High electric field intensity causes the rate of dissociation to exceed the rate of recombination.



These charges redistribute due to the electric field, forming heterocharge layers. The attraction of charges to the nearby electrode causes fluid motion. By designing electrodes to produce asymmetry of electric field, net flow results.



EHD Thin Film Boiling Experiment: Electrophoretic – Conduction Pumping

Objective:

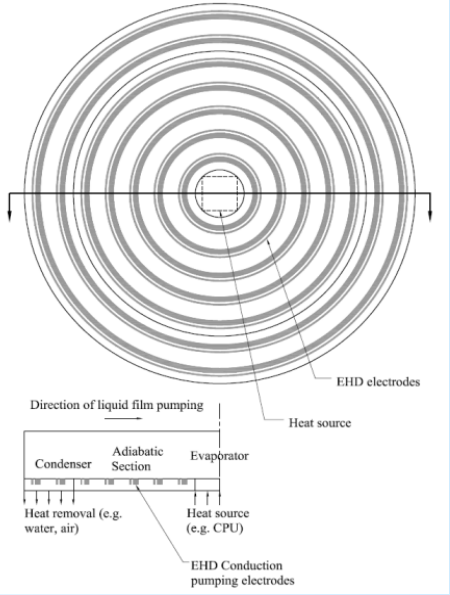
- Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:
  - The effects of microgravity on the electrically generated two-phase flow.
  - The effects of microgravity on electrically driven liquid film boiling (includes extreme heat fluxes).
- Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.

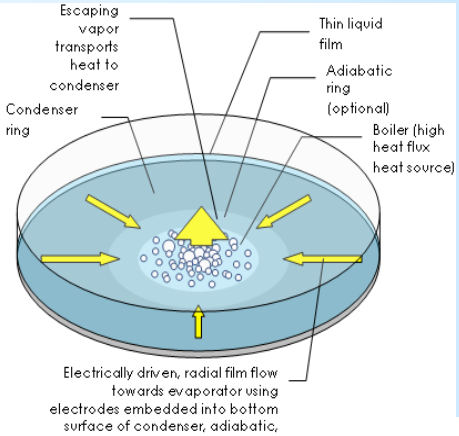
Relevance/Impact:

- Provides phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD, permitting optimization of heat transfer surface area to volume ratios as well as achievement of high heat transfer coefficients thus resulting in system mass and volume savings.
- EHD replaces buoyancy or flow driven bubble removal from heated surface.

Development Approach:

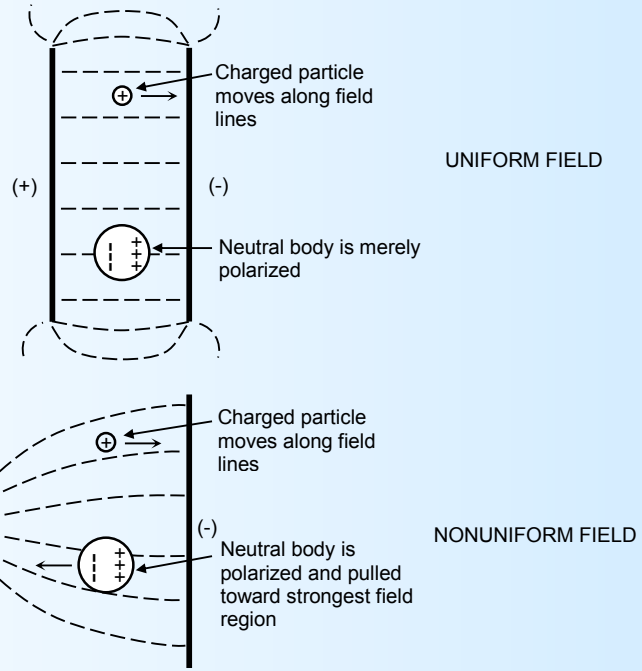
- Conduct preliminary experiments in low gravity and ground-based facilities to refine technique and obtain preliminary data for model development.
- ISS environment required to characterize electro-wetting effect on nucleate boiling and CHF in the absence of gravity.
- Will operate in the FIR – designed for autonomous operation.



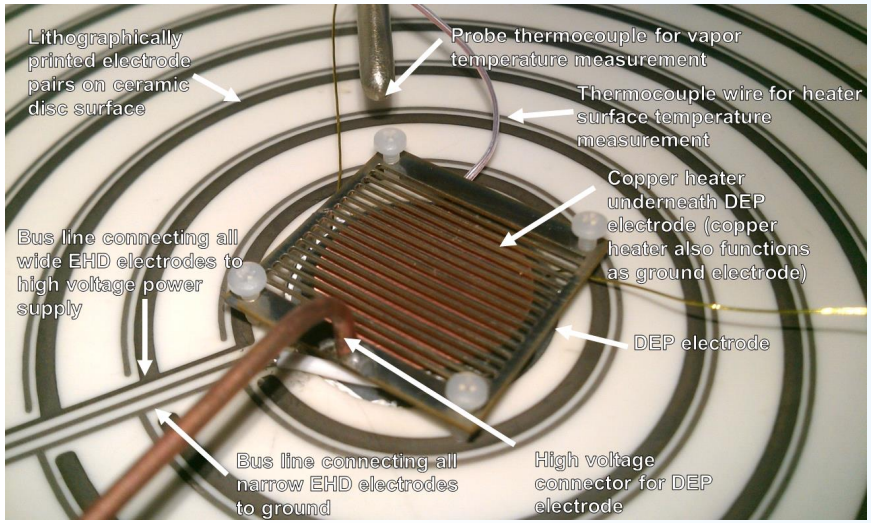


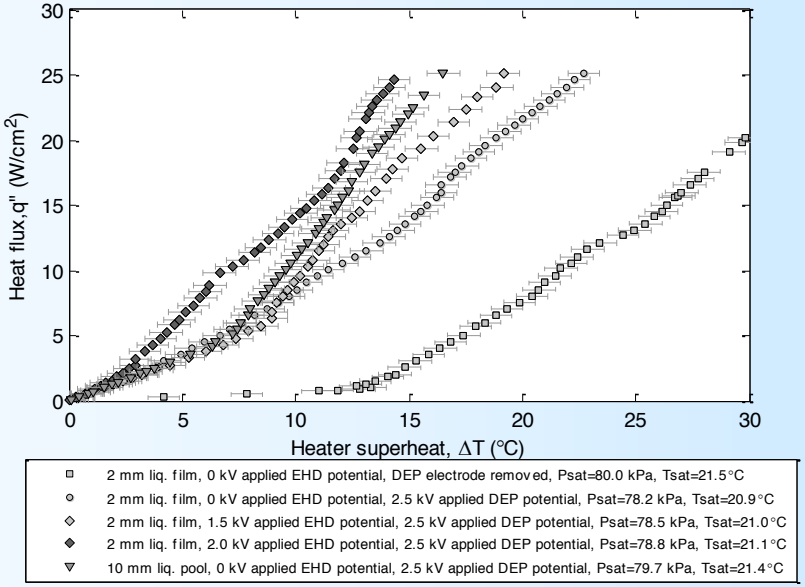
EHD Di-electrophoretic Force

$$\boldsymbol{F_{DEP}} = 2\pi a^3 \varepsilon_1 \left(\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\right) \boldsymbol{\nabla} |\boldsymbol{E}_e|^2$$



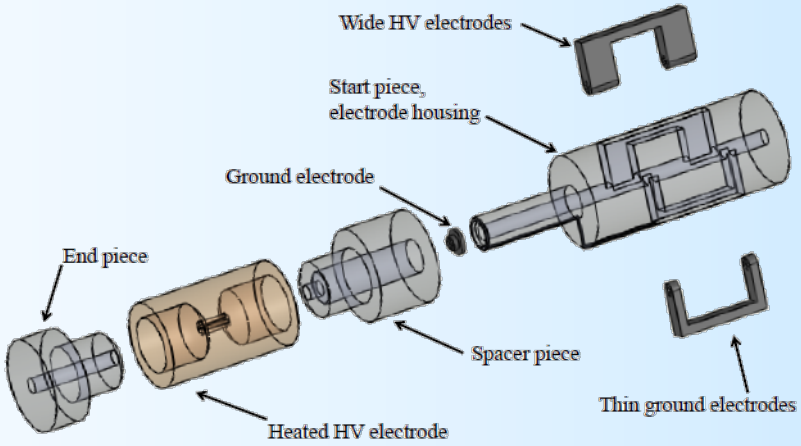
Combined Dielectrophoretic & Conduction Pumping

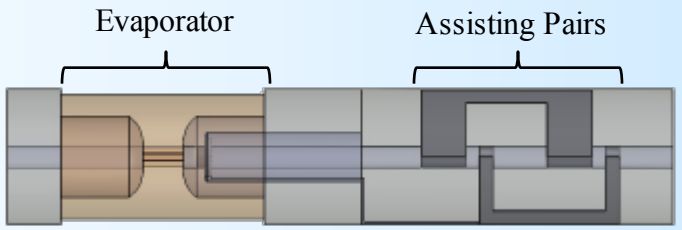




Micro-Scale EHD Enhanced Evaporation (NSTRF)

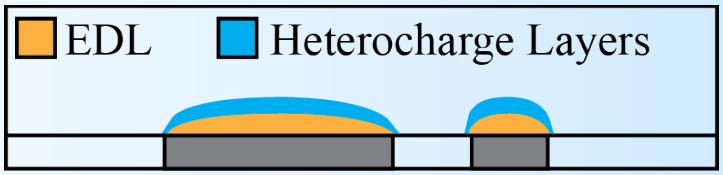
- Feasibility of embedded EHD enhancement
- Characterization of micro-scale perforations
  - Pressure generation
  - Flow rate generation
  - Flow regime estimate
  - Dry-out conditions
- Heat exchange loop
- Three electrode pairs
  - Two assisting upstream
  - One embedded in evaporator



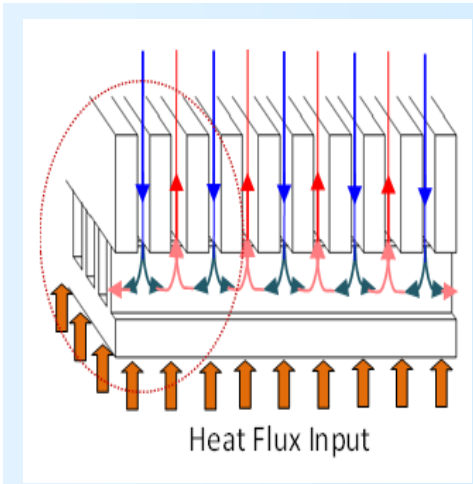


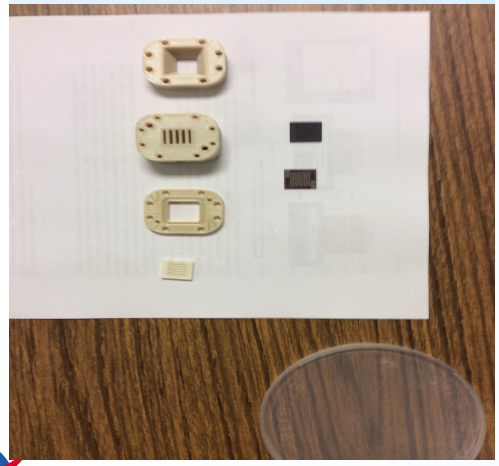
Nano-Scale Feasibility & Numerical Study (NSTRF)

- Modeling & simulation:
  - Electric double layer vs. heterocharge layers
  - Significant effects from the zeta potential
  - Capillary and electrophoresis effects
- Experimentation:
  - Manufacturing Process
  - Flow visualization
  - Single channel
  - Flow distribution



Heat Acquisition Concepts: Silicon Based EHD/Capillary Hybrid

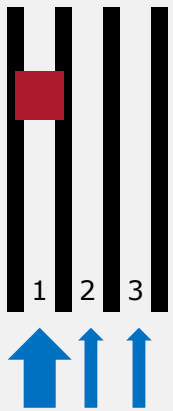




- Chip Integrated Component: High Temperature Heat Acquisition & Transport
  - Thin Film evaporation for high heat acquisition rates @ low temperature difference
  - Hybrid EHD/Capillary Fluid Management
- Silicon Manifolds Operations
  - Liquid (blue) to heat acquisition site
  - Vapor (red) transported to heat rejection site
  - Manifold channels ~ 100 microns (gravity independence & micro-scale applications)
  - Electrohydrodynamic enhanced: alleviate dry-out; insure gravity insensitivity
- Technologies to Enable the Concept
  - Capillary driven flow: self regulation of mass flow rate
  - Electrohydrodynamics (EHD): fluid management (liquid/vapor control), pump enhancement
  - DRIE to manufacture micro-channels
- Feasibility
  - Micro-scale capillary performance demonstrated
  - EHD micro-scale microgravity fluid management in micro-gravity campaigns (May 2012 & September 2013)
  - Manufactured Proof-of-Concept micro-channel EHD electrode system
  - Manufactured Capillary Proof of Concept hardware

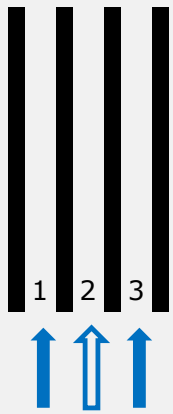
EHD Thermal/Fluid Management

Example 1



Increase flow to channel 1 due to temporary hot-spot in that region

Example 2



Overcome maldistribution by delivering supplemental pressure head to channel 2, restoring flow through that channel

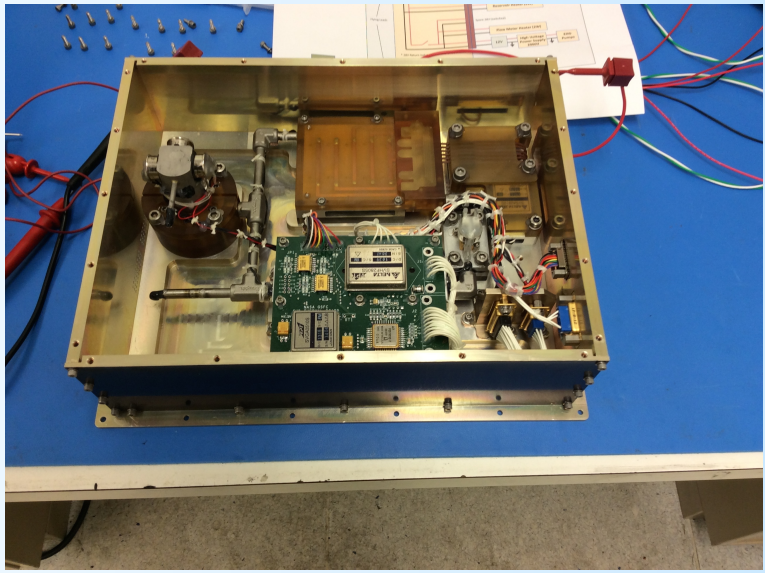
Channel Pressure Drop
- geometry
- mass flux
- heat flux

EHD Pressure Head must be of same order as channel Pressure drop to be effective

Technical Overview: Single Phase Thermal Management

EHD Thermal Multifunctional Plate

- Breadboard Hardware: STP-H5 Experiment
- Numerical Model
  - EHD Phenomena: Conduction Pumping
  - Design Tool
- Future Development
  - Smaller EHD Pumps
  - Higher Flow Rates
  - Intelligent Operations:
    - Variable Voltage Power Supply
    - Control System

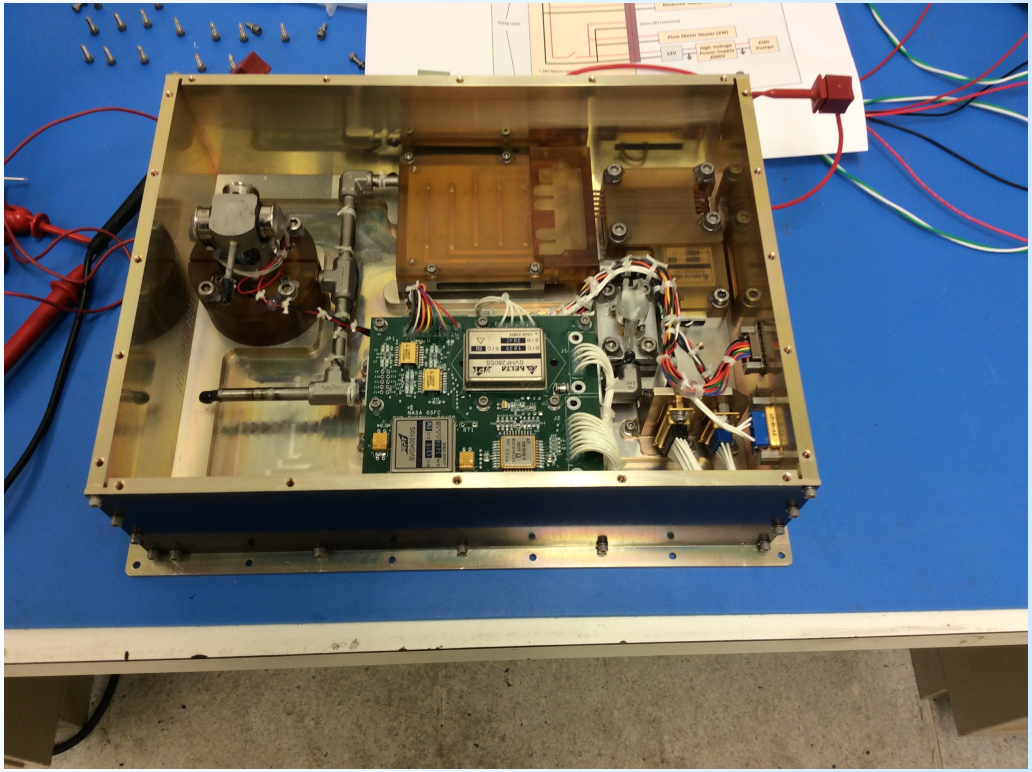


STP-H5 EHD Experiment: Proof of Concept & Life Test Loop

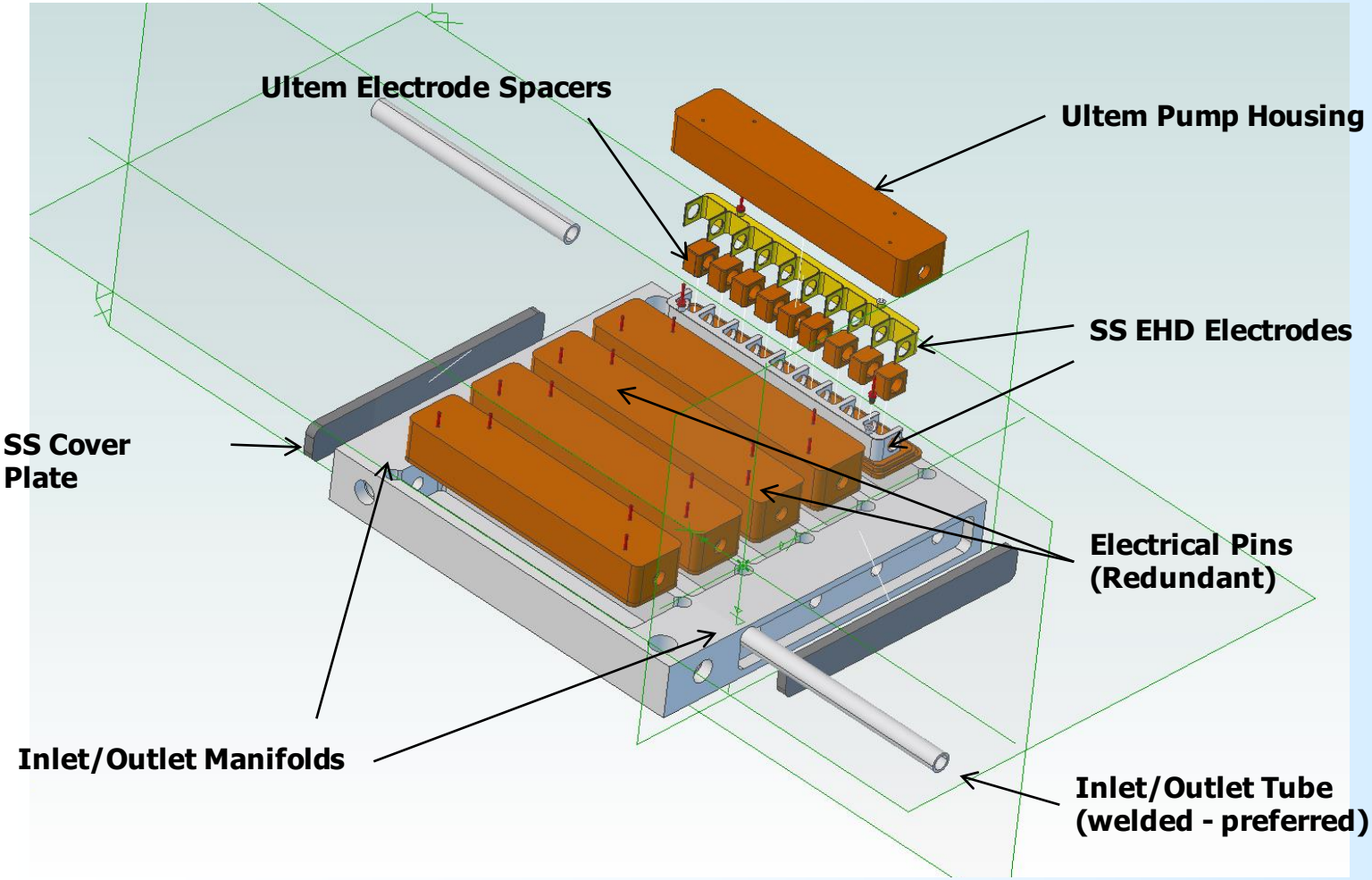
5 parallel EHD Pumps operating at 1000 Vdc
- ~ 0.5 g/s HFE 7100
- ~1000 Pa

Instrumentation
- Thermal Mass Flow
- 7 TCs

Status
- Flight Configuration
- S/C Environmental
- Launch: Summer 2016

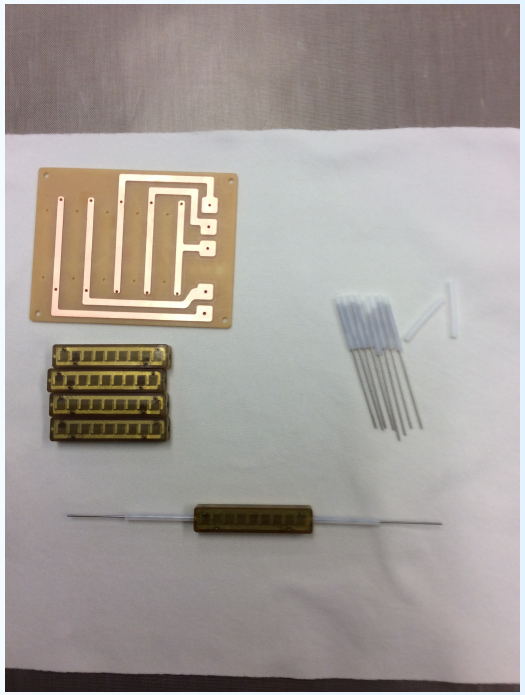


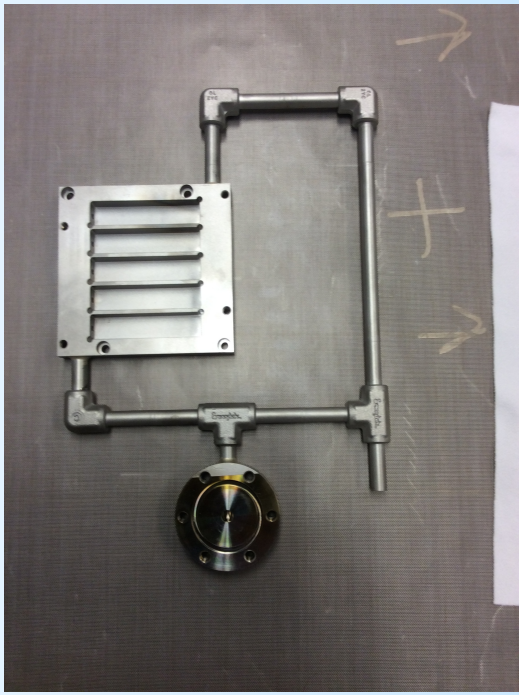
STP-H5 EHD Experiment: Prototype Multifunctional Plate

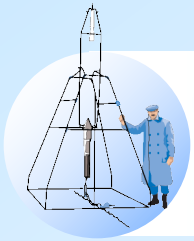


EHD Based Structural-Thermal Multifunctional Plate

- **Design & Fab EHD electrodes**
  - Electrode Fabrication: Hi Voltage & Ground
  - Smooth Sharp Edges
  - Insulate non-active surfaces
- **Integrate EHD electrodes**
  - Set into Ultem Container
  - Insert Ultem Spacers
  - Apply Epoxy/Closed out Pumps
- **Integrate into Multi-functional Plate**







EHD: Advantages & Constraints

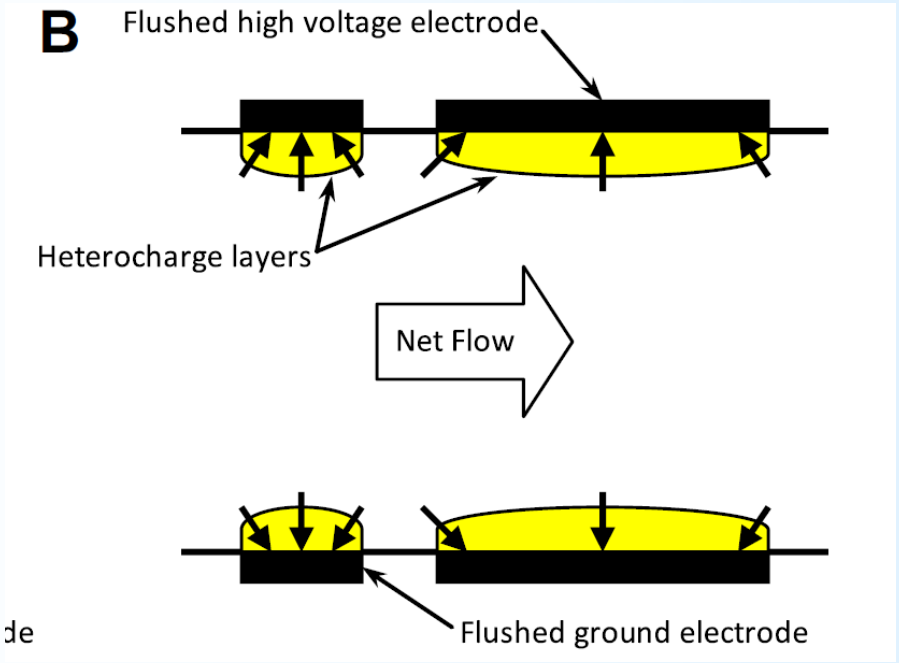
Advantages

- simple design
- light weight
- non-mechanical, no rotating machinery
- rapid and easy control of performance
- low power consumption
- low acoustic noise
- smart system

Constraints

- high voltage/electric field
- electric field interference
- electrically conductive fluids
- low pumping efficiency

EHD: STP-H5 EHD Conduction Pumps



EHD: Numerical Results – EHD Force (Preliminary)